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AN OVERVIEW OF RECENT RESEARCH RESULTS
IN CONTAMINANT HYDROGEOLOGY
AND IMPLICATIONS

John A. Cherry
Waterloo Centre for Groundwater Research
University of Waterloo
Waterloo, Ontario N2L 3G1

INTRODUCTION

Groundwater contamination is a major problem in nearly all industrialized countries. The problem has been developing for many decades but its existence generally went unrecognized prior to the 1980's. Groundwater in nearly all geological deposits travels slowly, less than 1 m per day and commonly less than 0.1 m per day. Thus, contaminants that enter the groundwater zone at waste-disposal sites, industrial sites, gas stations, septic systems and a wide variety of other common contaminant sources, normally take many years or decades to travel from the source to locations where they do recognizable harm, such as water-supply wells, springs or seepage zones feeding lakes or rivers. It is rare that groundwater contamination is discovered before harm occurs, even though the zone of groundwater contamination has been expanding for a long time prior to such discovery.

Much of what is now known about groundwater contamination has been learned during the past 10 years. With this new knowledge, the nature of the groundwater contamination problem has become clearer. The purpose of this paper is to briefly describe several major findings of recent years with comments on some implications of these findings.

DISPERSION

Dispersion is the process causing mixing of solutes in the groundwater zone. In sand or gravel aquifers where groundwater flow is primarily horizontal, a zone of contamination such as a plume undergoes mixing with uncontaminated water at its fronts. This frontal mixing is referred to as longitudinal dispersion. Mixing also occurs along the top and bottom of the plume, referred to as transverse vertical dispersion, and along the sides, referred to as transverse lateral dispersion. Field experiments conducted in a sand aquifer at Canadian Forces Base Borden, Ontario, indicate that, in this aquifer, dispersion in the two transverse directions is a very weak process resulting in almost no spreading of plumes laterally or vertically in the aquifer. Similar results have been obtained from other detailed dispersion studies in sandy aquifers elsewhere in Ontario, and on Cape Cod, Massachusetts. All of these studies and less detailed but nevertheless informative dispersion studies of sandy aquifers elsewhere have provided results consistent with the conclusion that dispersion in the transverse directions in sand and gravel aquifers is very weak.

An implication of this conclusion on transverse dispersion is that plumes of contamination emanating from point sources of contamination such as landfills, lagoons, chemical spills, leaky gasoline tanks and septic systems will commonly extend in the direction of groundwater flow as narrow discrete entities that follow the groundwater flow paths with little lateral or vertical spreading and with concentrations of some contaminants in the core of the plume that are not much

diminished by mixing. In other words, for many types of point sources contributing persistent and hazardous contaminants to the groundwater zone, dilution in the groundwater zone is generally not an effective means of rendering the contamination innocuous even at distances of many kilometres from the source. Another implication of the results of dispersion research is that effective monitoring to detect off-site migration of contaminants is generally more difficult than previously thought because, for early detection, narrow plumes require monitoring wells to be situated at critical locations that cannot be reliably predicted when the monitoring system is installed in the aquifer.

MOLECULAR DIFFUSION

Prior to several years ago, it was commonly thought that contaminants could be contained at waste disposal sites by lining the site with a layer of compacted clay and by covering the top of the waste-filled site with a layer of compacted clay. Compacted, water-saturated clay commonly has a hydraulic conductivity approaching 10^{-8} cm/s. Under a hydraulic gradient of 1, such clay has an average linear groundwater velocity of about 1 cm/yr. This suggests that it would take 100 years for relatively mobile contaminants to pass through a 1 metre thick compacted clay liner. When the effect of molecular diffusion is taken into account, however, the time for a mobile contaminant to pass through the liner is only about 5 years for a 1 m thick liner and about 7 days for a liner that has a thickness of 0.1 m.

Foster (1975) was the first to recognize the importance of the influence of molecular diffusion on contaminant migration in groundwater in low-permeability deposits. Subsequent to Foster's research in Britain, researchers have determined the effects of molecular diffusion on rates of contaminant migration in Ontario clays (Goodall and Quigley, 1977; Desaulniers et al. 1981; Crooks and Quigley, 1984; Johnson et al. 1988). For water-saturated clay to provide long-term containment of many types of contaminants, the clay layer must have a thickness of many metres or more and must be devoid of open fractures. Designers of waste-disposal facilities in North America have generally been slow to recognize the influence of molecular diffusion on contaminant migration in designs for waste-

isolation facilities which liners and caps are used to minimize escape of contaminants.

MOBILITY AND PERSISTENCE OF ORGANIC CONTAMINANTS

Prior to a decade or so ago, groundwater samples suspected of contamination were rarely analyzed for trace-level organic compounds. This was the case for several reasons, primary among them being the fact that the sophisticated laboratory facilities necessary to do such analyses were rare in water-quality laboratories in nearly all industrialized countries. These facilities did not come into significant use in Canada until the mid-1980's and even now only exist in a few provinces.

From trace-organic analyses of groundwater done in many countries, it is now known that (1) that groundwater contamination is much more common in most industrialized countries, than was previously suspected and (2) that, when groundwater is found to be contaminated to a degree potentially harmful to the health of water users, it is usually due to trace organic compounds. Nearly all organic contamination of groundwater has originated since the Second World War. In the 1950's the use of petroleum products and halogenated organic liquids rapidly became commonplace in cities, towns and villages.

The organic contaminants most frequently found in groundwater are listed on Table 1. Of these, the volatile organics are the most common because they are relatively persistent and have little affinity for adsorption in aquifers. Many of these compounds are carcinogens and have drinking-water limits specified in Europe or the United States at the parts per billion or tens of parts per billion level. Leakage of very little mass of such compounds from waste storage or disposal

facilities or from product storage containers at industrial sites can cause extensive contamination of aquifers at levels above such limits.

Analysis of groundwater in Canada for the compounds listed on Table 1 has lagged far behind many European countries and the United States because none of these compounds are included on the current federal drinking water standards issued in 1976, nor on provincial drinking-water standards, with the exception of Ontario where very recent changes have included some of them. As federal and provincial drinking water standards or guidelines in Canada are brought more in line with the recognition of the propensity for shallow groundwater to contain these organic compounds, we can expect analyses of well waters in Canada to include these compounds much more frequently.

The common aromatic hydrocarbons such as benzene, toluene and xylenes, derived from petroleum products often undergo fairly rapid biodegradation in aerobic groundwater zones. Biodegradation can cause the contamination to be restricted to a zone close to the contaminant source. Unfortunately, many contaminated aquifers are anaerobic, a condition that promotes the persistence and therefore extensive migration of these compounds.

The common chlorinated volatile organics such as tetrachloroethylene, trichloroethylene and trichloroethane generally do not biodegrade rapidly in aquifers. These compounds tend to slowly transform to less chlorinated but nevertheless hazardous compounds. In some cases the transformation products are more hazardous in drinking water than the original compounds.

DENSE IMMISCIBLE LIQUIDS

Many of the chlorinated compounds on Table 1 enter groundwater as immiscible liquids that are more dense than water. These oil-like liquids then dissolve and are transported by groundwater away from the source. Examples of dense immiscible liquids are chlorinated solvents, creosote, coal tar, and PCB liquids. Most common chlorinated solvents are less viscous than water and with their high density flow quickly downward through permeable soil into shallow aquifers, where they can settle below the water table on top of strata of low permeability. Small volumes of these immiscible liquids settled out in an immobile state in an aquifer can take a long time to disappear. For decades or even centuries the immiscible liquid will continue to dissolve in the aquifer and thereby feed contaminants to the flowing groundwater.

SOURCES OF CONTAMINATION

Of the many causes of groundwater contamination, only two will be discussed here, sanitary landfills and domestic septic systems. Leachate from sanitary landfills commonly contains a variety of mobile organic compounds, including many of those listed on Table 1. This seems to be the case even for landfills where disposal of hazardous industrial wastes are prohibited. The quantities of industrial organic liquids necessary to cause high concentrations in leachate are so small that prevention of their entry to municipal landfills is not feasible.

Leachate production in municipal landfills occurs for centuries. In wet climates such as in Ontario, the ability of landfills after closure to produce leachate containing hazardous levels of organic compounds listed on Table 1 is not known. I expect that the time scale is many decades or centuries. With such time scales, it is reasonable to expect that many, if not most, municipal landfills in Ontario will eventually cause offsite migration of some of the volatile organic compounds listed on Table 1. This statement is applicable even to municipal landfills of the most modern design if they are situated on geologic deposits than are not exceptionally impervious.

For a domestic on-site septic system to be approved in Ontario, the drainbed and subsoil must provide sufficient infiltration capacity for the subsurface to accept all of the effluent from the septic tank. In most hydrogeologic settings in Ontario, the effluent infiltrates to the water table and then moves primarily laterally in the groundwater regime.

Some contaminants, most notably sodium, chloride and nitrate, can travel large distances laterally, such as hundreds of metres, at relatively high concentrations. The drinking water limit for nitrate is 45 mg/L as NO_3^- . Research conducted recently by the University of Waterloo indicates that nitrate plumes from single-family homes situated on sand or gravel deposits or on fractured bedrock can be expected to cause off-property degradation of groundwater quality, with nitrate levels generally above the drinking water limit. The research has not yet progressed to the point where the type and persistence of aromatic and chlorinated organic contaminants in septic plumes can be predicted.

A septic system and a shallow water supply well serving the same household are common in Ontario and in most parts of North America even though the distance separating the two, which is mandated in regulations, is not adequate to prevent contamination of the well by the septic system. Commercial chemicals commonly sold in Ontario for cleaning of plumbing connected to the septic system contain hazardous organic compounds even though such compounds may cause severe groundwater contamination. In some states in the U.S.A., the sale of septic-system plumbing cleaners containing hazardous organic chemicals is banned.

CONCLUSIONS

In the past decade groundwater research and monitoring of groundwater supplies in industrialized countries has shown that groundwater contamination is a greater problem than was previously thought. The most common groundwater contaminants capable of causing significant adverse health effects on persons who drink the water are nitrate and volatile organics. These and some other contaminants in groundwater are commonly mobile and little attenuated in the groundwater because dilution (dispersion) and adsorption have only minor influences and biodegradation is commonly ineffective. The problem is exacerbated by the fact that dense immiscible liquids are ubiquitous in industry. Many of these liquids rapidly enter aquifers if spilled or leaked on the ground in even small quantities. Groundwater contamination is caused by chemicals entering the groundwater zone from many types of sources. Some causes are accidental; others are the normal product of the generally-accepted design of the system, such as municipal landfills and on-site septic systems. Monitoring of volatile organic compounds in groundwater is in an early stage in Canada. The true nature of groundwater contamination in Canada will become more evident as such monitoring becomes more widespread and frequent, as it already has in the United States and some European countries.

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Table 1: List of trace organic compounds most frequently found in contaminated groundwater

Volatile Organics

Benzene
Ethyl benzene
Toluene
Xylenes

Carbon tetrachloride
Chloroform
Dichloromethane

1,1,1-Trichloroethane
1,2 Dichloroethane
1,1-Dichloroethane
Chloroethane

Tetrachloroethylene
Trichloroethylene
Trans-1,2-dichloroethylene
1,1-Dichloroethylene

Chlorobenzene
Dichlorobenzenes (1,2-, 1,3- and 1,4- isomers)

Phenols

Total Phenols
Cresols (2-methyl, 3-methyl and 4-methyl isomers)
Pentachlorophenol
Phenol

Polynuclear Aromatic Hydrocarbons

Naphthalene

